GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO. 8, PAGES 1097-1100, APRIL 15, 1999

Rapid intensification and propagation of the dayside aurora: Large scale interplanetary pressure pulses (fast shocks)

Xiaoyan Zhou and Bruce T. Tsurutani

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

Abstract. We present two cases of abrupt dayside auroral brightenings and very fast auroral propagation using the POLAR UV imaging data. The brightenings occur first at noon and then propagate along the auroral oval towards dawn and dusk. Ionospheric speeds of 6 to 11 km/s are determined. The auroral brightenings and motion are associated with the arrival and propagation of interplanetary shocks/pressure waves. The brightening at noon occurs within minutes of the shock compression of the noon-time magnetopause. The speed of the auroral propagation in the ionosphere towards dawn and dusk corresponds extremely well to the solar wind downstream flow. Our model assumes that shocks/pressure waves compress the outer dayside magnetosphere, and plasma contained therein. This plasma compression leads to the loss cone instability, wave-particle interactions, and concomitant particle loss into the ionosphere.

1. Introduction

Variations in solar wind ram pressure have been shown to cause dayside aurora at Earth. During solar wind high pressure or pressure enhancements, postnoon bright spots can be the optical signatures of flux transfer events (FTEs) (*Sandholt*, 1987; *Lui and Sibeck*, 1991). *Lui et al.* (1995) have reported "auroral beads" and intense dayside aurora during a high pressure solar wind event. An interplanetary shock has been shown to be related to sudden dayside auroral brightening (*Craven et al.*, 1986). Energetic electron precipitation into the dayside auroral oval can occur immediately after a storm sudden commencement (SSC) (*Brown et al.*, 1961; *Egeland et al.*, 1994). Recent work (*Gonzalez and Tsurutani*, 1987) has shown that most SSCs are caused by interplanetary shocks associated with interplanetary coronal mass ejections (ICMEs).

The purpose of this paper is to study the ionospheric response to interplanetary shocks/pressure waves measured at WIND using the POLAR UV near-apogee imaging data. The global view of the dayside aurora and the high cadence (3 min) of POLAR images allows us to determine accurate timing relationships between interplanetary and ionospheric phenomena, observe and measure auroral ionospheric propagation velocities, and survey the global evolution of dayside auroral phenomena due to interplanetary shocks/pressure waves. We provide a model to relate shocks and auroral zone particle precipitation.

Paper number 1999GL900173.
0094-8276/99/1999GL900173$05.00

2. Observations of Interplanetary Shocks and Dayside Auroras

2.1 December 10, 1997 event

At 0432 UT December 10, 1997, the WIND spacecraft recorded an interplanetary (IP) shock. This is shown by the dashed line in Figure 1. The forward shock (with Mach number ~ 2.1) is identified by increases in the interplanetary magnetic field magnitude, solar wind bulk speed, proton density and proton thermal speed. Based on the shock orientation (provided by D. Berdichevsky, private communication, 1998) and propagation speed, we calculate that the IP shock should take ~ 53 min to travel from WIND to the Earth. It is estimated to arrive at the nose of magnetopause at ~ 0525 UT. The shock at WIND causes an increase in ram pressure P_{ram} ($1.16\rho_p V_{sw}^2$) from 2.0 to 7.5 nPa (where we assume $N_{He^{++}} = 4\% N_{H^+}$). The downstream static pressure P_{st} ($B^2/8\pi + nkT$) increases from 0.03 to 0.15 nPa. These parameters are shown in the bottom two panels of Figure 1. Although P_{st} is much smaller than P_{ram}, P_{st} increases by 5 times across the IP shock. Assuming magnetic flux conservation in the tail lobe, the size of the lobe will be reduced ~1/3 in diameter by this increased static pressure (see *Ho and Tsurutani*, 1997 and *Kokubun*, 1997 for distant tail examples). At the time when the shock arrives at Earth, GEOTAIL is in the dawnside magnetosheath at about (-3.7, -25.1, -0.5 R_E) in GSE coordinates. The proton density increases from 35 to 65 cm^{-3} at ~ 0528 UT while the plasma velocity increases from 250 km/s to 360 km/s. The enhanced plasma velocity is mainly along the negative X axis. The magnetic field intensity rapidly increases from 8 to 16 nT. If we assume the nose of dayside magnetopause is at 10 R_E prior to shock arrival, the shock should take 4 min to propagate from the nose to the GEOTAIL position. The shock should therefore have arrived at magnetopause at ~ 0524 UT. This is basically the same time as determined by our extrapolation and calculation using WIND data.

The dayside auroral brightening onset and subsequent propagation are shown in Figure 2, as viewed by the UVI. Typically, the UVI obtains an image every ~3 min with the same wavelength and with the same exposure time. In Figure 2, the images come from the LBHS filter, covering the wavelength band of ~140 -160 nm. The bottom color bar shows the auroral intensity in photons cm^{-2} s^{-1}. The near-noon auroral brightening is first detected in panel (c) when the near-noon auroral intensity suddenly increases by a factor of 3-4 (panels (a) and (b) are shown for comparison). The brightening is obviously an effect of the arrival of the IP shock. Based on these images, the IP shock arrived between 0523:24 UT and 0526:28 UT. Thus, there is an excellent agreement in timing with our calculation of the shock arrival, either from WIND or from

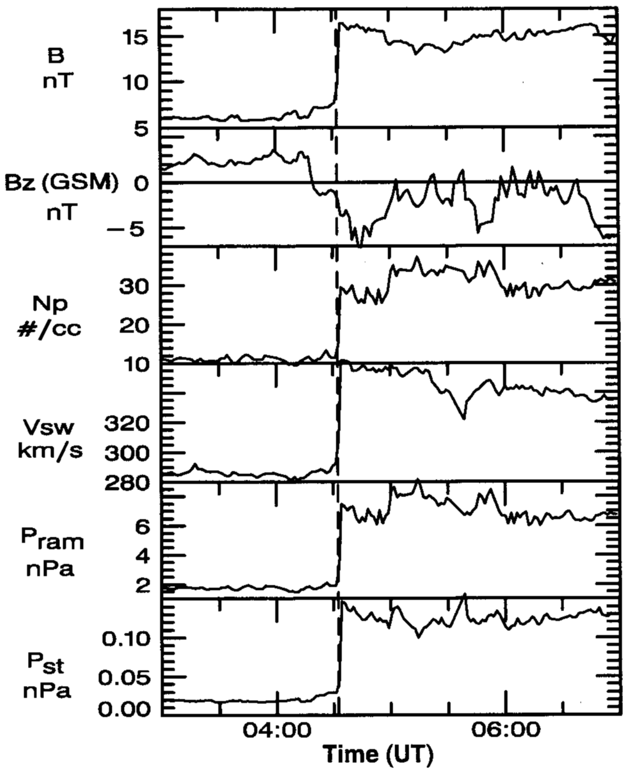

Figure 1. The interplanetary shock on December 10, 1997. At the time of the shock (~ 0432 UT), WIND was in the upstream solar wind at (207, 10, 23 R_E) in GSE coordinates.

GEOTAIL. In panel (c), the western leading edge is at ~ 9:30 MLT; the auroral brightening has a wider latitudinal extent and an intensity level of ~ 6 photons cm^{-2} s^{-1}. At 0529 UT, this western edge moves to ~ 4:30 MLT. Panel (d) shows auroral brightening along the arc at ~ 75 magnetic latitude. So from 0526 to 0529 UT, there is a westward propagation speed of ~ 11 km/s (westward means clockwise, eastward means anticlockwise looking down over the north pole). The western edge of the aurora arrives at ~ 1:30 MLT in panel (e). Using 73° as an average latitude, the calculated eastward longitudinal propagation speed from 0529 to 0532 UT is ~ 8 km/s. In panel (e) and (f) there are auroral intensifications near dusk. However it is difficult to measure the propagation speed based on the images for this case. During the event period in Figure 2, we do not find significant dayside latitudinal motion.

2.2 January 10, 1997 event

Another fast dayside auroral event is the January 10, 1997 event. An IP shock (with Mach number ~ 1.5) is observed by WIND at 0052 UT at an upstream distance of ~85 R_E. This is discussed in *Tsurutani et al.* (1998a) and *Arballo et al.* (1998). As shown in Figure 3, the auroral brightening occurs at a time between 0100:44 and 0103:48 UT. The calculated shock arrival time is ~ 0103 UT, which is again obtained based on a calculation using the shock orientation and propagation speed. As shown in panels (c) and (d), the noon aurora expands towards both east and west, while the auroral intensity increases about a factor of 2. The eastern edge propagates from ~ 12 MLT at ~ 0104 UT to ~ 14:30 MLT at ~ 0107 UT along 75° average magnetic latitude (actually the aurora is spread over a wider region, 70°-80° MLT). The average longitudinal propagation speed is ~ 6 km/s. With a similar speed, the eastern edge propagates eastward and reaches 18 MLT at 0110 UT (panel (e)). The western edge of the aurora propagates along the dawnside oval from ~ 10 MLT at 0104 UT to ~ 6 MLT at 0107 UT. Using 72° as an average latitude, the average auroral longitudinal propagation speed is ~ 11 km/s.

From Figure 3 panels (e) to (f), both duskside and dawnside auroral brightenings are intensified by about a factor of 2. During the event period in Figure 3, we do not find significant dayside equatorward propagation.

3. Model and Discussion

The dayside auroras shown in Figures 2 and 3 propagate very fast from local noon towards the flanks. The aurora longitudinal propagation speed in the December 10, 1997 event is ~ 9.5 km/s in the dawnside (on average). For the January 10, 1997 event, the dayside aurora propagates at ~ 6 km/s in the duskside and at ~ 11 km/s in dawnside. Because these values are based on images separated by 3 min, they are only approximate speeds. For more accurate ionospheric speeds, a higher cadence is required. The noon to dawn motion is in a direction opposite to electron drifts, thus this is an unusual auroral motion.

Our model for this auroral brightening and rapid propagation is that the increased solar wind ram and static pressures from the shock/pressure wave first compresses the LLBL and outer magnetosphere (see also *Craven et al.*, 1986). The compression first occurs at the magnetopause nose (~12 MLT) and then expands towards dawn and dusk as the shock/pressure wave moves downtail. Assuming that the first adiabatic invariant of the trapped plasma is conserved, compression of the outer magnetospheric field lines leads to an increase in perpendicular kinetic energy ($\varepsilon_\perp$) of the electrons (and protons) on those field lines. The enhanced $T_\perp/T_\parallel$ of the distribution function will result in loss cone instability. The growth of electromagnetic whistler mode waves (*Tsurutani et al.*, 1998b) leads to enhanced electron pitch angle scattering, filling of the particle loss cone, and results in electron loss into the upper ionosphere.

The dayside auroral magnetic latitude location and region in ionosphere should correspond to the L shells which have been strongly affected by the compression of the magnetosphere. In this scenario, the location and propagation of the dayside auroral forms should result from the propagation of the compression of the outer parts of the magnetosphere. This process is illustrated in the schematic in Figure 4.

When a planar shock or solar wind pressure pulse arrives at the nose of the magnetopause, the magnetopause is compressed and moves earthward. This is indicated in the first two panels. When pressure balance between the magnetospheric fields and the solar wind is achieved, the earthward motion of the magnetopause will cease. The ram pressure and the increased static pressure both squeeze the magnetopause inwards towards the Earth on the flanks (where the ram pressure is not perpendicular to the normal of the magnetopause). The magnetospheric compression propagates in the down-tail direction along with the shock/pressure wave. Wherever the fields are compressed, the loss cone instability will occur (assuming that there are sufficient pre-existing fluxes of trapped particles) and cause auroral brightening.

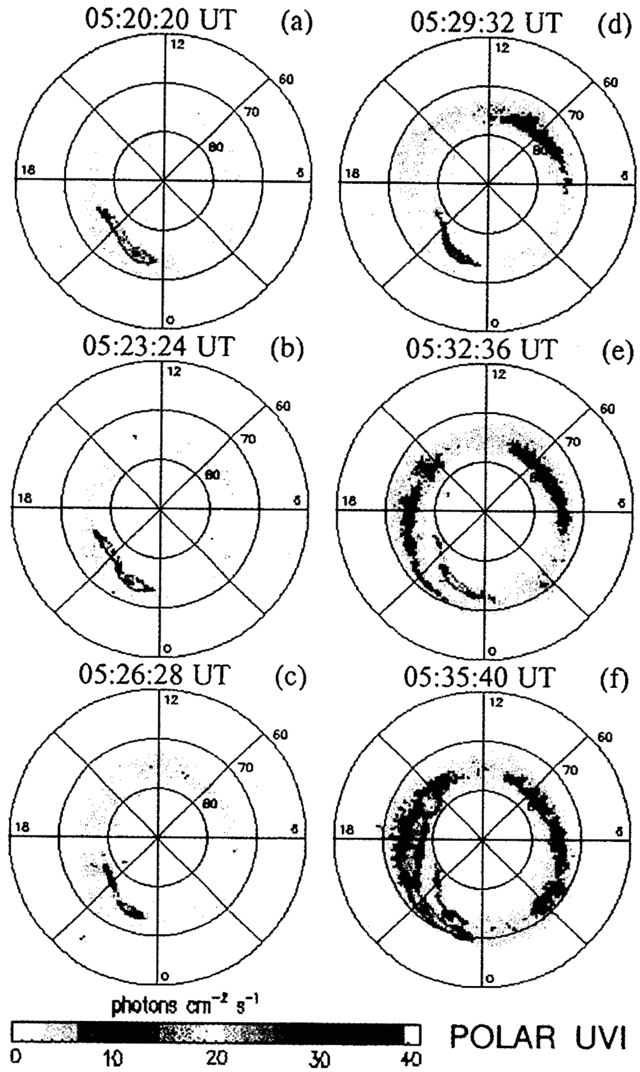

Figure 2. The rapid dayside auroral propagation event of December 10, 1997. The image exposure time is 36.8 sec. There is 3 min and 4 sec between images. A magnetic coordinate system is used. Noon is at the top and dawn on the right. Dayglow and background noise have been removed from the images. Time evolves from panel (a) to (f) (top down and then to the right). Panel (c) shows the auroral onset just after the shock arrival.

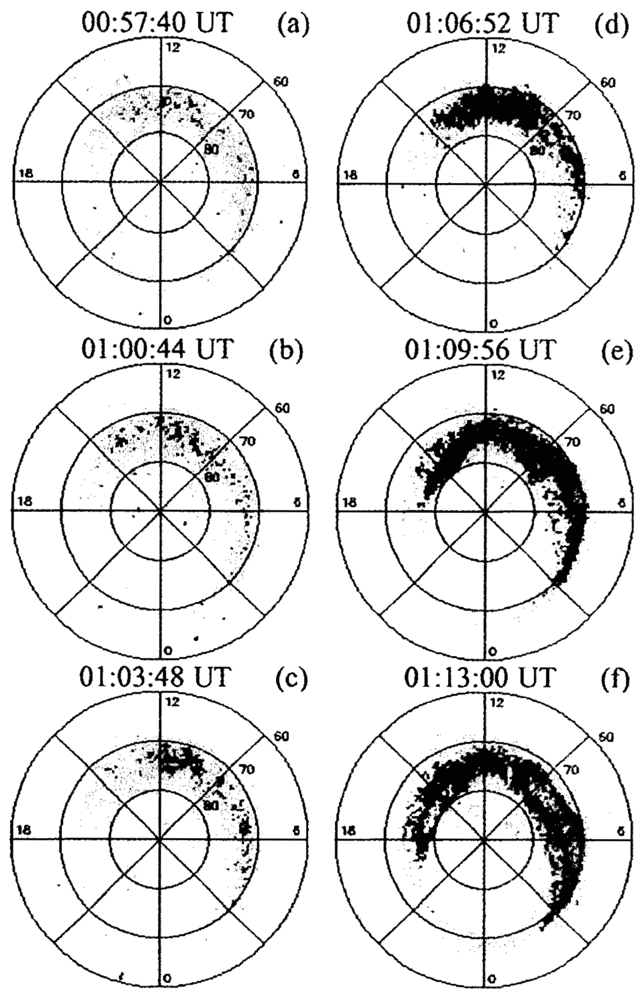

Figure 3. The rapid dayside auroral propagation event of January 10, 1997. The images come from the LBHL filter (~170 nm). The exposure time, spacing between images, color bar scale and format are the same as in Figure 2.

In this scenario, we assume that the auroral zone magnetic field lines are closed and map to the outer magnetosphere at approximately the same local time. Thus, the propagation of the compressed magnetopause position (A-A′ in Figure 4) should be at a speed which is constant with the speed of the auroral propagation. For the December 10, 1997 event, the dawnside auroral propagation speed is ~ 9.5 km/s on average. The corresponding speed along the magnetopause should be ~ 367 km/s. This speed is in good agreement with the GEOTAIL magnetosheath speed of ~ 360 km/s. For the January 10, 1997 event, Interball-Tail is at (-19, 19, 10 R_e) GSM with Vx=-300 km/s. The predicted speed by the duskside auroral propagation (from panel (d) to (e)) is ~ 280 km/s.

4. Implications of the Results

We have shown two events of abrupt auroral brightenings and rapid motion from noon to dusk and noon to dawn. The brightenings are associated with the arrival of IP shocks/pressure waves at the magnetopause. The rapid longitudinal auroral propagation towards both flanks are matched with the speed of the interplanetary shock or the high speed pressure pulse moving tailward. We predict that these rapid dayside aurora onsets and global ionospheric propagation events are present in ground all-sky camera or photometer scanner data.

From the UV images presented here, we cannot tell exactly where the aurora occurs: on closed or open (or both) magnetic field lines? From our model and from the view of *Lorentzen et al.* (1996), one would expect that shock related auroral enhancements would occur equatorward of the cleft/cusp aurora on the dayside. We encourage examination of ground-based auroral observations to determine what type of auroral enhancements are present during magnetosphere/magnetosheath compression events.

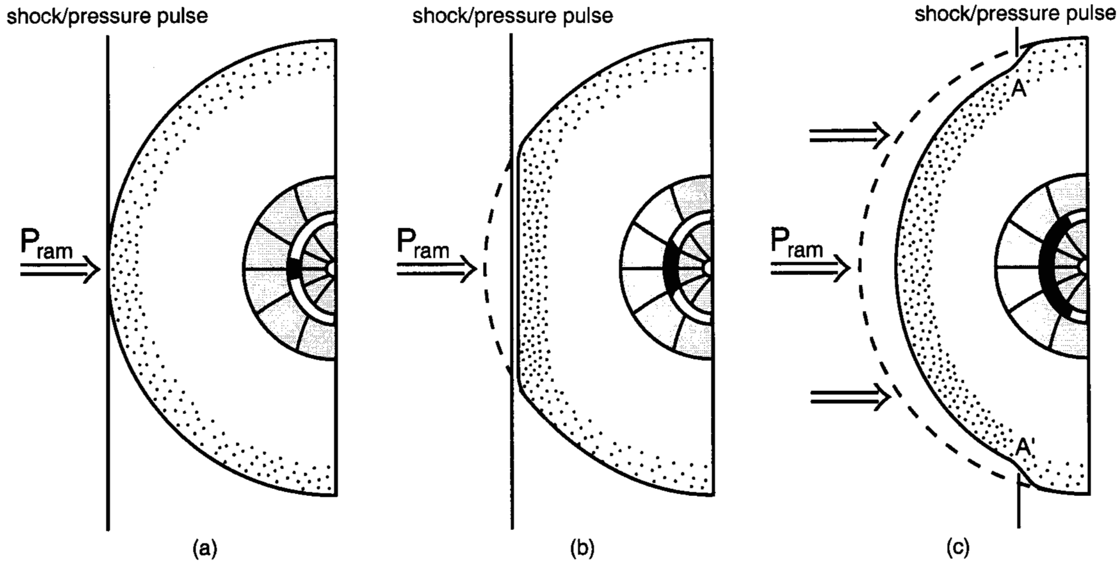

Figure 4. A model of magnetospheric compression caused by an IP shock or a solar wind pressure pulse. This schematic is a polar view of the dayside magnetopause and auroral oval. The magnetopause is compressed by an IP shock or a pressure pulse (vertical line) arriving from the left. The shock propagates down tail with a temporal sequence from (a) to (c). In panel (a), a noon auroral brightening occurs just after the shock/pressure pulse impinges upon the nose of the magnetopause. In panels (b) and (c), the noon auroral brightening expands towards both dawn and dusk as the magnetopause/magnetosphere compression proceeds in the tailward direction.

When an IP shock or a solar wind pressure pulse impinges on the Earth's magnetopause, fast auroral propagation should occur starting from local noon and move towards the dawn and dusk flanks. The propagation speed will vary from event to event and depends on the local time and the speed of the interplanetary shock/pressure pulse event. In this scenario the auroral speed due to the magnetospheric compression should be fastest near local noon and the slowest in the nightside hemisphere. Interplanetary velocities three times greater than the events reported here have been previously discussed in the literature. The intensity of auroral brightenings depends on the increase in ram and static pressure of the interplanetary events and the preexisting magnetospheric particle fluxes. Clearly the fastest interplanetary events will have the greatest ram pressure and one would expect the most dramatic auroral effects.

Acknowledgment. Portions of this paper represent work done at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, under contract with the National Aeronautics and Space Administration. We thank G. Rostoker and Y. Kamide for very helpful scientific discussions. We thank the WIND SWE and MFI principal investigators, K. Ogilvie and R.P. Lepping, for use of the data. We especially thank J.K. Arballo for helping in the data processing and software support. X.-Y. Zhou would like to thank the National Research Council for the award of a Resident Associateship at the Jet Propulsion Laboratory.

References

Arballo, J.K., C.M. Ho, G.S. Lakhina, B.T. Tsurutani, X.-Y. Zhou, Y. Kamide, J.-H. Shue, S.-I. Akasofu. R.P. Lepping, C.C. Goodrich, K. Papadopoulos, A.S. Sharma, and J.G. Lyon, Pseudobreakups during January 10, 1997, *International Conference on Substorms-4*, ed. Y. Kamide and S. Kokubun, pp.315-318, Terra Sci., Tokyo, 1998.

Brown, R.R., R.R. Hartz, B. Landmark, H. Leinbach, and J. Ortner, Large-scale electron bombardment of the atmosphere at the sudden commencement of a geomagnetic storm, *J. Geophys. Res.*, 66, 1035-1041, 1961.

Craven, J.D., L.A. Frank, C.T. Russell, E.E. Smith, and R.P. Lepping, Global auroral responses to magnetospheric compressions by shocks in the solar wind: two case studies, in *Solar Wind-Magnetosphere Coupling*, edited by Y. Kamide and J.A. Slavin, pp.367-380, Terra Scientific, Tokyo, 1986.

Egeland, A., W.J. Burke, N.C. Maynard, E.M. Basinska, J.D. Winningham, and C.S. Deehr, Ground and satellite observations of postdawn aurorae near the time of a sudden storm commencement, *J. Geophys. Res.*, 99, 2095-2108, 1994.

Gonzalez, W.D., and B.T. Tsurutani, Criteria of interplanetary parameters causing intense magnetic storms (Dst< -100 nT), *Planet. Space Sci.*, 35, 1101-1109, 1987

Ho, C.M., and B.T. Tsurutani, Distant tail behavior during high speed solar wind streams and magnetic storms, *J. Geophys. Res.*, 102, 14165-14176, 1997.

Kokubun, S., Dynamics of the magnetotail during the magnetic storms: Review of ISEE 3 and GEOTAIL observations, in *Magnetic Storms, Geophys. Monogr. Ser.*, vol. 98, edit by B.T. Tsurutani, W.D. Gonzalez, Y. Kamide, and J. K. Arballo, AGU, Washington, D.C., pp.117-130, 1997.

Lorentzen, D.A., C.S. Deehr, J.I. Minow, R.W. Smith, H.C. Stenbaek-Nielsen, F. Sigernes, R.L. Arnoldy, and K. Lynch, SCIFER-Dayside auroral signatures of magnetospheric energetic electrons, *Geophys. Res. Lett.*, 23, 1885-1888, 1996.

Lui, A.T.Y., and D.G. Sibeck, Dayside auroral activities and their implications for impulsive entry processes in the dayside magnetosphere, *J. Atmos. Terr. Phys.*, 53, 219-229, 1991.

Lui, A.T.Y., R.E. Elphinstone, J.S. Murphree, M.G. Henderson, H.B. Vo, L.L. Cogger, H. Luhr, S. Ohtani, P.T. Newell, and G.D. Reeves, Special features of a substorm during high solar wind dynamic pressure, *J. Geophys. Res.*, 100, 19059-19107, 1995.

Sandholt, P.E., Interplanetary and geophysical effects of a coronal transient, *Ann. Geophys.*, 5A, 219-229, 1987.

Tsurutani, B.T., J.K. Arballo, G.S. Lakhina, C.M. Ho, J. Ajello, J.S. Pickett, R.P. Lepping, W.K. Peterson, G. Rostoker, Y. Kamide, and S. Kokubun, The January 10, 1997, auroral hot spot, horseshoe aurora, and first substorm: A CME loop?, *Geophys. Res. Lett.*, 25, 3047-3050, 1998a.

Tsurutani, B.T., J.K. Arballo, G.S. Lakhina, C.M. Ho, B. Buti, J.S. Pickett, and D.A. Gurnett, Plasma waves in the dayside polar cap boundary layer: Bipolar and monopolar electric pulses and whistler mode waves, *Geophys. Res. Lett.*, 25, 4117-4120, 1998b.

Xiaoyan Zhou and Bruce. T. Tsurutani, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109 (e-mail: zhou@jplsp.jpl.nasa.gov, btsuruani@jplsp.jpl.nasa.gov)

(Received: November 13, 1998; revised: January 25, 1999; accepted: February 15, 1999.)